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13. ABSTRACT (Maximum 200 words)

This report contains information on the items of equipment acquired with this DURIP award including name, cost, manufacturer and special circumstances regarding their acquisition. It also contains a summary of each research project on which the equipment has been and will be used. These projects are of major significance to the Department of Defense and include topics such as reconfigurable tuners and band-stop filters using MEMS switches, micromachined cavity diplexers and loaded cavity resonators, reconfigurable electromagnetic bandgap resonators and microwave circuits on low resistivity silicon substrates. A list of associated publications is also provided.

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INSTRUMENTATION FOR THE DEVELOPMENT OF RECONFIGURABLE MICROWAVE/MM-WAVE FGC PASSIVE ELEMENTS USING MEMS SWITCHES FOR "SMART" SYSTEMS ON A CHIP

FINAL REPORT

A. Instrumentation information

This grant was directed towards acquiring an Agilent 85107B fully integrated vector network analyzer system and a Cascade Microtech RF-1 microwave probe station to develop various novel microwave/mm-wave passive circuits, including reconfigurable structures using MEMS switches, for "smart" system on a chip military applications. The Agilent 85107B is a complete system configured with a 50 GHz synthesized sweeper and scattering parameter test set (a picture of the actual acquired system can be seen in Fig. 1). The RF-1 is a probe station that includes manual positioners and probe mounts, a microscope with an associated mounting kit and a vacuum pump with a vacuum manifold kit (a picture of the actual acquired system can be seen in Fig. 2). Cost information and other details of the purchased equipment are listed in Table 1. It is interesting to note here that due to delays in the manufacturing of optical components, the delivery of the probe station was delayed significantly from the original date quoted by the manufacturer (approximately 2 months). Both pieces of equipment were located in the Electrical and Computer Engineering Department at the University of Arizona.

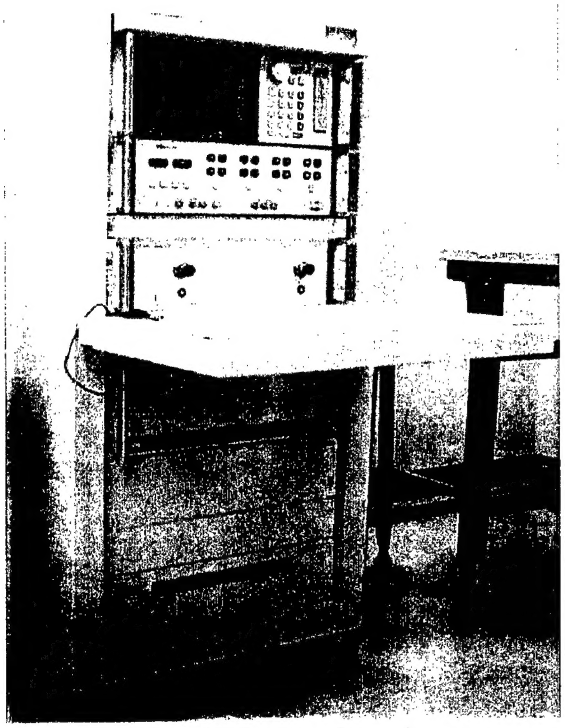


Fig. 1 Acquired network analyzer system

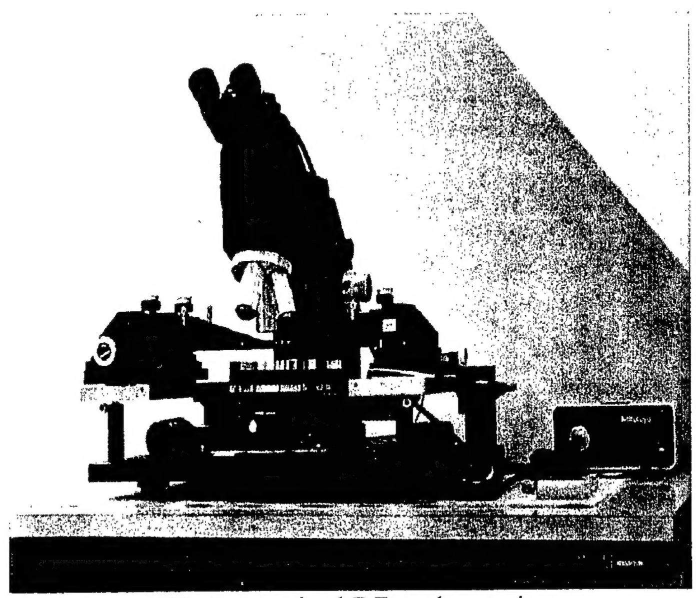


Fig.2 Acquired RF probe-station

Equipment	Manufacturer	Cost	Comments
Network Analyzer (45 MHz-50 GHz)	Agilent Technologies	$118,120.00	Includes time domain capability and 3.5 mm calibration kit
RF Probe Station	Cascade Microtech	$30,190.00	Includes 3 microwave positioners, microscope with light and vacuum pump with manifold kit

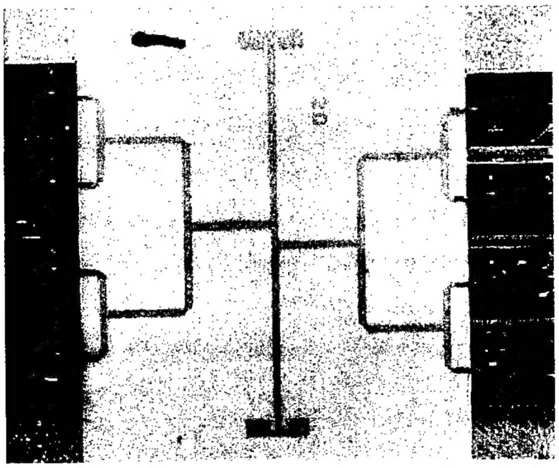
Table 1. Information regarding the network analyzer and RF probe station.

B. Summary of research projects

Both the network analyzer and RF probe station were utilized in a variety of research projects involving graduate and senior undergraduate students. The purchase of the above equipment gave a unique opportunity to students at The University of Arizona to study and investigate microwave structures and circuits of importance to the Department of Defense, as well as train them in microwave measurements. A brief summary of each project is given below including current projects.

B.1 Reconfigurable double stub tuner utilizing MEMS devices

The goal of this project was to develop a planar tuner that can match a wide variety of loads for frequencies between 10 and 20 GHz. Such a component is an essential part for reconfigurable, low cost wireless and satellite communication networks and radars, tunable navigation and positioning systems and seekers for smart weapons. The design was based on a double stub tuner concept, were each stub was realized with a digitized capacitor bank. Each bank consisted of different capacitors (in this case open-end stubs since we are dealing with frequencies above 10 GHz) connected via MEMS switches to the main transmission line that connects to the load. Depending on which switch is activated a different capacitor was selected, matching a different load. Since the MEMS switches are electrostatically activated, this will eventually allow for a reconfigurable tuner or "smart" tuner that is controlled by a digital processor. Designs with 2,3 and 4 capacitors per stub at center frequencies ranging from 10-20 GHz were explored. In order to produce a prototype within a short period of time collaboration with the Raytheon MEMS group in Dallas was pursued. Figure 3 shows a picture of the fabricated "4x4" tuner at 20 GHz and figure 4 shows measured and simulated results. Measurements revealed that the tuner could match loads with real parts from 1.5 to 160 Ω and imaginary parts from −106 to 134 Ω at 20 GHz, covering areas in all 4 quadrants of the Smith chart. The tuner also worked well and within expectations at 10 and 15 GHz. Based on these findings, a paper was presented at the 2001 International Microwave Symposium [1] and a journal paper will be submitted in the very near future. The student who worked on the project (Ms. Krista Lange) received her MS degree. Future studies include the replacement of the longitudinal open-end stubs with radial stubs and the implementation of cantilever beam (metal-to-metal contact) switches.



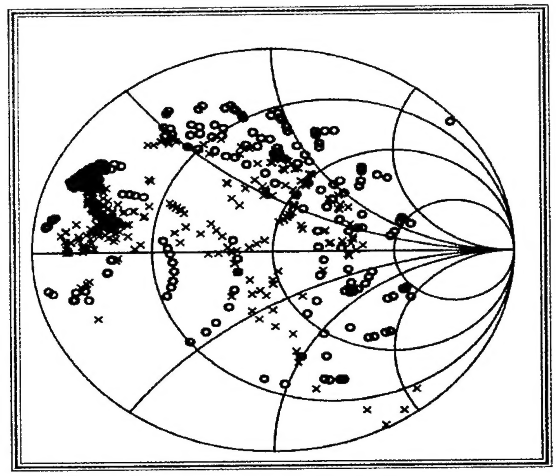


Fig.3 Photo of fabricated tuner

Fig. 4 Measured (x) and simulated (o) results at 20 GHz

B.2 Reconfigurable band-stop filter using MEMS devices

The goal of this project is to develop an X-band (8-12 GHz) reconfigurable band-stop filter. A 3-pole design with three high impedance stubs terminated in different capacitor values is being investigated. Each capacitor is implemented with a radial stub for purposes of compactness. Full-wave simulations have been completed, and have revealed that it is possible to develop an 8-14 GHz bandstop filter with 6 MEMS switches and 6 radial stubs. The size of the filter is 8mm x 7mm and the rejection at the center frequency varies between 30 dB to 15 dB for frequencies from 8 to 14 GHz, respectively. Fabrication and experimental characterization of the first prototype is expected to be completed by the end of this year. Optimization of the design will then follow with a goal to increase the rejection across the entire band. The development of such a filter is expected to lower the cost of receivers used in military radars and other communication systems, while maintaining excellent performance and achieving tunability, low power consumption and compactness.

B.3 Micromachined silicon diplexer at 20 GHz

The goal of this project was to develop a single-pole monolithic diplexer with narrow-band and low-loss performance at 20 GHz. The diplexer comprised of two silicon micromachined cavities with different resonant frequencies (19 and 21 GHz). The input signal was split via a Tee-junction to two paths coupling energy into the cavities via coupling slots. The cavities were micromachined with wet etching techniques inside a 1-mm thick silicon wafer. Agreement between simulations and measurements was excellent. Measured results indicated a bandwidth of 1.1% and an insertion loss of 1.4 dB for the receive channel (18.64 GHz), and a bandwidth of 1.53% with a loss 1.0 dB for the transmit channel (20.47 GHz). Isolation was better than 26 dB. The quality factor of a single cavity was measured to be Q=890 around 19 GHz, which is the highest ever reported. The overall diplexer size was 37 mm x 10.3 mm x 2.5 mm and the results pave the way for the development of a more mature multi-pole diplexer. Based on these findings, a paper was presented at the 2000 European Microwave Conference [2], while a journal paper will be published in the IEE Proceedings [3]. The project was part of Mr. Michael Hill's Ph.D. dissertation.

B.4 Reduced size micromachined resonator at 5.7 GHz

The goal of this project was to develop a reduced size high-Q silicon planar resonator at 5.6-5.8 GHz for wireless LAN and other applications. Previous research had shown that micromachined air-cavities in silicon wafers yield high quality factors, but become extremely large below 8 GHz. For this reason, the cavity was filled with a high dielectric constant material such as Alumina (ε_r=9.8) and BST (ε_r =70). The Alumina resonator had a size of 18.4mmx9.5mmx1.0mm and yielded a Q_u=640 at 5.65 GHz and an insertion loss of 6.6 dB with a 36.5 MHz bandwidth. The BST resonator had a size of 7mmx3.5mmx1mm and yielded Qs ranging from 152 to 197 and an insertion loss of 5.35 dB with an 81 MHz bandwidth. Measured results agreed very well with theoretical calculations and full-wave simulations. This research showed that the limiting factor for achieving even higher quality factors was the dielectric loss of the filling material, as well as alignment of the feed wafer, the dielectric and the cavity wafer. The student that worked on this project (Mr. Christophe Tavernier) received his MS degree. A paper was presented at the 2000 European Microwave Conference [4] and a journal paper has already been submitted [5].

B.5 Reconfigurable electromagnetic-bandgap X-band cavity resonators

The goal of this project was to develop high-Q reconfigurable resonators operating in X-band (8-12 GHz). While micromachined cavity resonators provide high quality factors for microwave frequencies, it is not possible to change or tune their resonant frequency due to the "static" nature of the cavity walls that define the cavity dimensions. For this reason, in this project the continuous cavity walls were replaced with rows of via-holes that prohibit propagation along the lattice of a signal at the frequency of the cavity resonance. By selecting which rows are connected to ground the width or length of the cavity can be changed, thus changing the resonant frequency. Initial experiments were conducted on Duroid based resonators and showed that the rows of vias can confine the electromagnetic fields very well and yield resonator performance similar to that with the continuous walls. Based on these results, a reconfigurable Duroid resonator was developed with 4 rows of vias. Measurements yielded Qs of 448 and 274 for the 10.6 GHz and 8.63 GHz resonances, respectively. Further improvement of the lower frequency quality factor is possible with optimization of the via-hole design. It is expected that selection of the via-holes will be possible with activation of MEMS switches. This project was part of Mr. Michael Hill's Ph.D. dissertation and 2 journal papers have already been published [6]-[7].

B.6 Microwave circuits on low-resistivity silicon substrates for wireless interconnects

The goal of this project was to investigate and develop finite ground coplanar circuits operating between 30-35 GHz on a low resistivity silicon substrate for wireless interconnects. It is know that low resistivity silicon produces high loss microwave and mm-wave circuits due to the conducting nature of the substrate. For this reason, a thin layer of polyimide (20 μm) is spun on top of the silicon wafer and all circuits are fabricated on top of the polyimide. As a first step band-pass and low-pass filters, as well as folded slot antennas were studied. The low-pass filter exhibited a loss of 0.74 dB and 5.4 dB at 2 GHz and 10 GHz, respectively. The band-pass filter (2-pole) yielded an insertion loss of 2.76 dB at 26.48 GHz with a return loss of

22 dB. The folded slot antenna exhibited a resonance at 30.5 GHz with a return loss of 14.6 dB. Measurements of radiation patterns yielded an E-plane with a main lobe at broadside and strong surface waves around 83 degrees, as well as a smooth H-plane with a maximum at broadside. Further study of the antenna and other components (phase shifter, mixer and oscillator) is currently under way. Four senior undergraduate students were involved in this project in order to fulfill their senior capstone design course requirement. One paper has already been presented at the 2001 RFIC symposium [8] and another one will be presented at the 2001 silicon topical meeting [9].

C. Conclusions

It is quite clear that none of the above described research projects would have been pursued or realized without the DURIP support of the Army Research Office. For this reason the PI is grateful to ARO and Dr. James Harvey. The PI has accepted a faculty position with Georgia Tech starting in August of 2001. The equipment purchased under this DURIP grant will be transferred to Georgia Tech that will compensate The University of Arizona for the matching funds provided. ARO has already approved this transfer.

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